The behavioral effects of index insurance in fisheries

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Fisheries are vulnerable to environmental shocks that impact stock health and fisher income. Index insurance is a promising financial tool to protect fishers from environmental risk. However, insurance may change fisher's behavior in ways that exacerbate problems from overfishing. We provide the first theoretical application of index insurance on fisher's behavior change to predict if index insurance will incentivize higher or lower harvests in unregulated settings. The direction of harvest changes depends primarily on: the ability for fishers to mitigate production risk, the correlation between sources of risk, and the type of risk protected by the insurance contract. Simulating from parameters estimated for four Norwegian fisheries shows index insurance could increase harvest by a median of 15% or decrease harvest by 4%. Before widespread adoption, careful consideration must be given to how index insurance will incentivize or disincentivize overfishing.

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1 Introduction

Fishing is a vital economic engine to coastal communities and is the primary source of protein for millions of people (Sumaila *et al.* 2012; Teh and Sumaila 2013; FAO 2020). Supporting these communities requires protection from enormous degrees of environmental risk. Environmental fluctuations directly impact fishers of all scales from large industrial vessels to small scale subsistence fishers.

Marine heatwaves provide a clear example of how environmental variability impacts biological and economic productivity of fisheries. Marine heatwaves increase animal thermal stress diminishing reproductive ability (Barbeaux *et al.* 2020), stunting growth (Pandori and Sorte 2019), pushing species outside their usual habitats (Cavole *et al.* 2016), and may directly increase mortality (Smith *et al.* 2023). Expanding fish habitat ranges increase costs when they move beyond the fishing grounds of established ports (Rogers *et al.* 2019). The variability from marine heatwaves alone impacts 77% of species within economic exclusion zones and reduces maximum catch potential by 6% (Cheung *et al.* 2021). Marine heatwaves are often accompanied by harmful algal blooms and diseases leading to additional fishery collapses (Oken *et al.* 2021).

Whereas some sources of environmental variability affect fish stocks, others affect the direct extraction of fish. Rolling seas and high wind speeds make it more difficult to harvest (Alvarez *et al.* 2006) in addition to raising the danger to crew and vessel (Heck *et al.* 2021). Storms threaten coastal infrastructure crucial to fishing communities (Sainsbury *et al.* 2019).

Fishers are highly sensitive to risk, especially income risk, and demonstrate risk aversion despite working a seemingly risky profession (Smith and Wilen 2005; Holland 2008; Sethi 2010). Individual choices by fishers and fishery management mitigate environmental risk. Fishers actively avoid fishing in destructive weather at the expense of lost income (Pfeiffer 2020). Individual efforts to mitigate risk include choosing consistent, known fishing grounds over risking exploring unknown spots (Holland 2008) or choosing to fish less after storms and hurricanes (Pfeiffer 2020; Pfeiffer *et al.* 2022). However, these efforts are unlikely to completely eliminate risk. Additional financial tools may be needed to address income risk as a result of environmental fluctuations (Sethi 2010; Kasperski and Holland 2013). There is growing interest in developing new financial tools to alleviate financial and income risk for coastal communities (Wabnitz and Blasiak 2019; Sumaila *et al.* 2020).

Insurance may be an ideal financial tool for risk management in fisheries as it is scalable, protects against environmental shocks, and smooths income for fishers (Mumford *et al.* 2009; Watson *et al.* 2023). Currently, insurance in fisheries is primarily used to protect assets such as vessel hulls or fishing gear (FAO 2022). Insurance coverage could be expanded to include income variability originating from weather and biological productivity shocks. An insurance product covering these environmental risks could improve fisher welfare and promote community resilience (Maltby *et al.* 2023).

Policy makers have begun advocating for new fisheries insurance programs modeled after agricultural crop insurance programs (Murkowski 2022). Index insurance is one such product extolled by practitioners as a prime candidate for fisheries productivity insurance (Watson *et al.* 2023). Index insurance gained traction in agriculture as an effective alternative to indemnity crop insurance in developing countries because it had lower administrative cost, minimizes moral hazards, and does not require claim verification (Collier *et al.* 2009; Carter *et al.* 2017). Whereas indemnity crop insurance requires an assessment of loss to an individual, index insurance uses an independent measure as the basis for issuing payouts to all policyholders. The difficulty in establishing individual indemnified loss for individual fishers is a key reason for the rise of index insurance in prominence over indemnity insurance (Herrmann *et al.* 2004; Watson *et al.* 2023).

An example pilot program through the Caribbean Oceans and Aqauculture Sustainability Facility (COAST) pays out a set amount to fishers when indices of wave height, wind speed, and storm surge indicate a hurricane (Sainsbury *et al.* 2019). Triggers are the index values that initiate a payout.

One crucial area that remains under studied is the potential influence of insurance on fishers behavior. Moral hazards are decisions by insured agents that they would not otherwise take if they were uninsured (Wu *et al.* 2020). Although practitioners appear to favor index insurance on the belief that it avoids moral hazard (RARE 2021), there are two components to insurance moral hazard: "chasing the trigger" and "risk reduction" that must be considered. "Chasing the trigger" is the directed behavior of policyholders to increase the likelihood of a payout. For example, a fisher might choose to fish less to receive an indemnified harvest insurance payment. Index insurance completely eliminates this moral hazard if the index is independent of fisher choices, e.g. fishers cannot affect sea surface temperature. "Risk reduction" occurs when policyholders possess an insurance contract that protects them from risk, leading them to reoptimize their decisions. Index insurance remains susceptible to this element of moral hazard. In fisheries, one possible response is to fish more when insurance covers losses. Another response could be the insurance payout sufficiently covers fishing income loss that disincentives additional fishing pressures particularly during ecological vulnerable stages. All preliminary analyses of fisheries index insurance are missing rigorous assessment of this element of moral hazard.

Previous studies articulated hypothetical examples of moral hazards in fishery indemnity insurance programs, such as encouraging fishers to fish in foul weather or to not exit the fishery after a bad year of harvest (Herrmann *et al.* 2004; Watson *et al.* 2023). However, neither study built testable models to uncover risk reduction moral hazard impacts on fisheries. This paper is the first to build a theoretical model that will capture changes in fishers harvesting decisions stemming from the provision of an index insurance contract. Fisheries remain vulnerable to overfishing. It is imperative to ensure new policies do not provide perverse incentives that degrade long term sustainability by encouraging greater fishing pressures.

Research from agriculture provides compelling evidence that behavior change ought to be expected in fisheries. Index insurance applied to grazing in pasture commons shows clear evidence of risk reduction moral hazards leading to environmental degradation (Müller *et al.* 2011; Bulte and Haagsma 2021). Other studies from agriculture find that the impact of insurance on environmental sustainability depends on the underlying risk reducing or increasing qualities of inputs used in production (Ramaswami 1993; Mahul 2001; Mishra *et al.* 2005). Risk increasing (decreasing) inputs will always lead to increased (decreased) input use with insurance. Numerous agricultural studies confirm insurance incentivizes changes in input use (Horowitz and Lichtenberg 1993; Babcock and Hennessy 1996; Smith and Goodwin 1996; Goodwin *et al.* 2004; Mishra *et al.* 2005; Cai 2016; Deryugina and Konar 2017; Claassen *et al.* 2017; Elabed and Carter 2018; Sibiko and Qaim 2020; Stoeffler *et al.* 2022; **Sloggy2025?**).

Fisheries differ in crucial ways, thus motivating an analysis of the behavioral effects of index insurance in this new setting. Stock abundance is a necessary input in fisheries production, and is a major source of production uncertainty. Stochastic growth of residual fish stocks leads fishers to have limited information on the complete amount of fish available to harvest each season. Farmers have clear potential yields given their own agronomic practices before planting (Grassini *et al.* 2011). The realization of weather throughout the season create deviations from potential yield. Fishers are constrained by random realizations of fish abundance.

Additionally, the act of harvesting is random in fisheries. With perfect knowledge of the amount of fish in the ocean, a fisher must still choose the right time and location to catch the fish. The spatiotemporal dimension of fishing decisions fishers have to make differ from the set grids of agriculture (Reimer *et al.* 2017). Stochasticity surrounds each extraction decision that could be exacerbated by weather shocks.

We present a new model that introduces both stock and extraction risk in fisheries to better accommodate existing individual fisher risk mitigation strategies. With an adaptive, more flexible specification of production, we test how index insurance will incentivize behavior change in fisheries with multiple sources of risk. Index insurance has the potential to enhance conservation or impede it depending on the resulting change in harvest. Fish abundance has a simple relationship to harvest so that decreases in harvest will correspond to increases in fish stocks. Therefore, analyzing only the effects of insurance on fisher input use is sufficient to determine the overall direction of changes in fish stocks.

We find that index insurance will change fisher behavior, but the outcomes depend on three factors. First, input extraction risk effects remain important determinants of fisher behavior. As an agriculture, insurance will generally lower risk decreasing input use and thus harvest, while insurance leads to more risk increasing inputs. However, because of the unique stock risks of fisheries, a novel interaction arises where fishers may use more risk decreasing inputs with insurance.

The second factor drives the new outcome where risk reducing inputs increase. The correlation between extraction and stock shocks creates a unique tradeoff. Higher stock shocks lead to more fish available to harvest. Those same shocks may increase extraction risk. Fishers inherently want to expand production to capture these good years even while they prevent extraction risk through risk decreasing choices. Insurance continues to incentivze the reduction of extraction risk decreasing inputs, but lowering input use gives up the potential to capture more fish during goods years. Thus, whether insurance leads to an increase or decrease depends on the relative productivity of inputs and their variance reduction effects.

The last factor is the type of risk protected by the insurance contract. If shocks are uncorrelated, insurance contracts that protect against stock risk will always lead to more input use. Even when correlated, there is a tendency for insurance contracts built on stock risk to increase harvest greater than contracts built on extraction risk. Currently, most proposed insurance contracts are examining triggers based on stock risk, such as sea surface temperature or chlorophyll-a (Watson *et al.* 2023).

The insights dervived from this paper will ideally inform the design of sustainable insurance contracts in fisheries. The vulnerability of fisheries neccessiates careful consideration of the potential behavioral effects of insurance contracts.

The remainder of the paper structured as follows. Section 2 details a new stochastic production function for fisheries that integrates both stock and production risk. Section 3 proves that index insurance will change fisher behavior, but the outcomes are ambiguous and depend on the risk effects of inputs and the interaction between shocks. Section 4 extends the theoretical model to account for multiple inputs in fishing that reflects the decisions of fishers in the empirical setting. Section 5 numerically estimates potential harvest changes with an index insurance program. Parameters are calibrated with an application to Norwegian fisheries through the results of Asche *et al.* (2020). Section 6 concludes with a discussion on the suitability of fishery index insurance.

2 Risky Production in Fisheries

We define a novel fishery stochastic production model with two sources of variability. Our model extends traditional fishery production models that only account for biological stock risk to include an additional source of uncertainty that affects fisher extraction. Fishers are now able to make risky decisions along more than one margin, which better reflects the complexity of fisher decisions and risk mitigation abilities.

$$y = f(X)\hat{B} + \theta f(X) + \omega h(X) \tag{1}$$

Equation 1 is a general form of fishery production that separates the extraction risks from stock risk. The stock risk is captured by $\theta f(X)$ where $f(X)$ is always a concave harvest technology function, $f_x(X) > 0, f_{xx}(X) < 0$.[1] Fishers use a vector of m inputs $X \in \{x_1, x_2, ...x_m\}$ that interacts with a stochastic stock of fish, $\tilde{B}$. The stock of fish is additively separatable, $\tilde{B} = \hat{B} + \theta$, with a mean component $\hat{B}$ that fishers expect given factors such as prior year escapement, and a mean-zero variance component θ. This formulation is often referred to as process error, where randomness could originate from weather shocks in the current period or measurement error (Tilman *et al.* 2018; Merino *et al.* 2022). Greater realizations of stock lead to corresponding increases in production. Weather can affect stock productivity by changing sea surface temperature, upwelling, or primary production. We define this component of production risk the stock risk effect, θ.

However, fishers are also exposed to other forms of risk beyond biological stock risk. Foul weather, regulatory changes, or inherent variability in extraction all impact fisher production. All other forms of risk not captured by stock risk are extraction risk, ω. Fisher inputs may interact with these risks through the extraction risk effect function $h(X)$.

The extraction risk effects of inputs are captured by $\omega h(X)$, where $h(X)$ can either increase or decrease risk, $h_x(X) \lesseqgtr 0$. Fishers make decisions that mitigate some production risk (Holland 2008) through technical expertise and the skill of captains that limit "luck" in fishing (Kirkley and Strand 1998; Kompas *et al.* 2004; Alvarez *et al.* 2006). Fishers also consider the impact of gear on production variance before fishing (Eggert and Tveteras 2004). Inputs that lower risk will have $h_x(X) < 0$ and are called risk decreasing, while inputs that increase risk will have $h_x(X) > 0$ and are called risk increasing in line with Just-Pope Production functions in agriculture (Just and Pope 1978)[2].

Index insurance will change fishers exposure to overall risk. The separation of more fisher controlled extraction risk and independent stock risk allows fishers to consider more margins of risk. Our production model allows fishers to be exposed to stock risk while incorporating some margin for adjustment in extraction risk. In the next section, we explore how index insurance affects fisher decisions along each margin contingent on the type of risk the insurance protects against.

[1] Common specifications of $f(X)$ are Cobb-Douglas or linear harvest from Gordon-Schaefer.

[2] Observe that $f(X)$ is always risk increasing when $f(X)$ is an increasing, concave function.

3 Index insurance in fisheries

We assume fishers derive utility from profits and are price takers (Equation 2) and that harvest is the numeraire good so its price is exactly equal to 1:

$$\pi = f(X)\hat{B} + \theta f(X) + \omega h(X) - c(X) \tag{2}$$

We assess the potential behavior implications an insurance contract to protect against biological, θ, or production risk, ω. We assume insurance companies have perfect information on both distributions, although in reality, insurance agents may only have sufficient information on one of the risks to form a suitable contract. For example, biological shocks may be easier to observe and monitor compared to individual extraction shocks.

We create insurance lotteries through contracts that use either ω or θ as the trigger. For notational ease, we present the model with a contract built on ω, but the structure is interchangeable with contracts built on θ. Insurance pays out a constant amount γ if $\omega < \bar{\omega}$. By allowing contracts on only one of the random variables, we introduce basis risk as a contract triggered solely on ω cannot protect against all the biological risk of θ. No prior study has examined the effect of basis risk on the optimal input use before, but it is has been observed to change the optimal amount of insurance coverage in agriculture (Clarke 2016; Lichtenberg and Iglesias 2022). We bookend extremes of basis risk by examining cases where θ and ω are completely independent or perfectly correlated to analytically derive results with basis risk. We can test variations in basis risk more finely in the numerical simulations.

Actuarially fair insurance implies the premium, ρ, paid in both lotteries to be the probability of receiving a payout times the payout amount, $\rho = J(\bar{\omega})\gamma$, where $J(\omega)$ is the cumulative distribution of the representative shock. Additionally, if we set the trigger in either contract to zero to indicate any time shocks negatively impacts total production, profits will enter corresponding bad and good states. Now we can compare the impacts of input risk effects on the expected marginal profit between states. This will help separate harvest changes originating from insurance and profitability. By aligning production states with index triggers allows for a more seamless integration with insurance in the next step. This leads to the following two lemmas:

Lemma 3.1. *Expected marginal profit is higher in bad states for risk decreasing inputs when contracts are built on extraction risk ω and shocks are uncorrelated.*

$\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x_m} > 0$ *if* $h_{x_m}(X) < 0$.

Otherwise, risk increasing inputs lead to higher expected marginal profit in the good states.

$\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x_m} < 0$ *if* $h_{x_m}(X) > 0$

Contracts built on θ will always lead to higher expected marginal profits in the good state regardless of extraction risk effects when shocks are uncorrelated

$\frac{\mathbb{E}[\partial\pi|\theta<\bar{\theta}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|\theta>\bar{\theta}]}{\partial x_m} < 0$

Lemma 3.2. *When shocks are perfectly correlated, expected marginal profit is always higher in the good state when an input, x_m, is risk increasing and ambiguous when x_m is risk decreasing. This hold regardless of the chosen index.*

$\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x_m} < 0$ *if* $h_{x_m}(X) > 0$

And, $\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x_m} \lesseqgtr 0$ *if* $h_{x_m}(X) < 0$.

The proofs of Lemma 3.1 and Lemma 3.2 are included in the appendix.

Risk aversion is a necessary condition for insurance to be desirable (Outreville 2014). Therefore, we assume fishers are risk averse to income shocks through a concave utility function. Fishers will maximize their own expected utility across lotteries by selecting inputs with an exogenous insurance contract (Equation 3). Fishers consider the joint distribution $j_{\omega,\theta}$ of shocks to maximize their utility.

$$
\begin{aligned}
U \equiv \max_X \mathbb{E}[U] = \int_{-\infty}^{\infty} \Bigg[& \int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta) u(\pi(X,\hat{B},\theta,\omega) + (1 - J(\bar{\omega}))\gamma) d\omega \\
& + \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta) u(\pi(X,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) d\omega \Bigg] d\theta
\end{aligned} \tag{3}
$$

We first examine the effects of index insurance on optimal input decisions for one input, $X \in \{x\}$. The first order condition that solves Equation 3 is then:

$$
\begin{aligned}
\frac{\partial U}{\partial x} &= \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta) u_x(\pi(x,\hat{B},\theta,\omega) + (1 - J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega \\
&+ \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta) u_x(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega \Bigg] d\theta \\
&= 0
\end{aligned} \tag{4}
$$

To find the effect of insurance on optimal input, we use the implicit function theorem to examine how input choice varies with the insurance payout γ (Equation 5). We use γ to test insurance effects, because a marginal change in the payout alters the income smoothing effect of insurance on utility instead of the change in the distribution of states through a change in the trigger $\bar{\omega}$. A higher γ at all trigger levels means a fisher would receive more compensation in the event of a loss, but have to pay more in all other years. Therefore, γ provides a stronger measure of the value of insurance than changes to the trigger level $\bar{\omega}$.

$$\frac{\partial x^*}{\partial \gamma} = -\frac{\frac{\partial U}{\partial x \partial \gamma}}{\frac{\partial^2 U}{\partial x^2}} \tag{5}$$

By the sufficient condition of a maximization problem, $\frac{\partial^2 U}{\partial x^2}$ is negative so we can focus solely on the numerator to sign the effect. The numerator of Equation 5 is given by:

$$\begin{aligned} \frac{\partial U}{\partial x \partial \gamma} = \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} & j_{\omega,\theta}(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) + (1-J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(1-J(\bar{\omega})) d\omega \\ & + \int_{\bar{\theta}}^{\infty} j_{\omega,\theta}(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(-J(\bar{\omega})) d\omega \Bigg] d\theta \end{aligned} \tag{6}$$

We examine the input decisions of insurance contingent on the source of risk the insurance is designed to protect. Proposition 3.1 provides a result on the uncorrelated case to isolate insurance effects more clearly before moving to the correlated case in Proposition 3.2.

Proposition 3.1. *For feasible index insurance contracts specified at trigger $\bar{\omega} = 0$, when ω and θ are independent random variables, optimal fisher input will decrease with an increase in γ when $h_x(x) < 0$ and increase when $h_x(x) > 0$.*

For feasible index insurance contracts specified at trigger $\bar{\theta} = 0$, when ω and θ are independent random variables, optimal fisher input will always increase with an increase in γ.

Proof. We focus on an index of ω first. The steps to solve for a θ index are identical.

Independence of ω and θ allows us to factor out the joint distribution in the integral of Equation 6 into the respective marginal distributions.

$$\begin{aligned} \frac{U}{\partial x \partial \gamma} = \int_{-\infty}^{\infty} j_\theta(\theta) \Bigg[\int_{-\infty}^{\bar{\omega}} & j_\omega(\omega) u''(\pi(x,\hat{B},\theta,\omega) + (1-J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(1-J(\bar{\omega})) d\omega \\ & + \int_{\bar{\omega}}^{\infty} j_\omega(\omega) u''(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(-J(\bar{\omega})) d\omega \Bigg] d\theta \end{aligned} \tag{7}$$

Suppose insurance fully covers the loss between states, then utility in the good state and bad state are equal to each other so that we can factor out like terms in Equation 7. For brevity, all like terms including γ are indicated by the $u(\cdot)$.

$$
\begin{aligned}
\frac{U}{\partial x \partial \gamma} = &\int_{-\infty}^{\infty} j_\theta(\theta) J(\bar{\omega})(1 - J(\bar{\omega})) u''(\theta, \cdot) \\
&\times \left[\int_{-\infty}^{\bar{\omega}} j_\omega(\omega) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\omega - \int_{\bar{\omega}}^{\infty} j_\omega(\omega) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\omega \right] d\theta
\end{aligned} \tag{8}
$$

The first term outside the brackets is negative by the definition of concave utility, $u'' < 0$. Lemma 3.1 demonstrates the interior of the brackets is positive when $h_x(x) < 0$ as the marginal profit in the bad state is greater than the marginal profit in the good. Therefore, index insurance will decrease input use for risk decreasing inputs when the extraction shocks are independent of stock shocks.

When $h_x(x) > 0$, the interior sign of the brackets in Equation 8 is negative by Lemma 3.1. Therefore, index insurance will increase input use for risk increasing inputs.

A contract built with θ will follow the same steps with the only difference being in the integral bounds and the differential variables as shown in Equation 9. The 2nd term of Equation 9 is always negative by Lemma 3.1. Therefore, a contract built on θ will always increase optimal input use when θ and ω are uncorrelated

$$
\begin{aligned}
\frac{U}{\partial x \partial \gamma} = &\int_{-\infty}^{\infty} j_\omega(\omega) J(\bar{\theta})(1 - J(\bar{\theta})) u''(\omega, \cdot) \\
&\times \left[\int_{-\infty}^{\bar{\theta}} j_\theta(\theta) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\theta - \int_{\bar{\theta}}^{\infty} j_\theta(\theta) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\theta \right] d\omega
\end{aligned} \tag{9}
$$

□

Our specification of fishery index insurance shows that index insurance may result in behavior change in fisheries. The direction of change from risk effects follows the same outcomes as demonstrated by Mahul (2001) and Ramaswami (1993) when stock and extraction risks are independent, and the trigger is defined in terms of extraction risk. Insurance provides risk protection lowering the necessity of risk decreasing inputs, therefore reducing their use and overall harvest. Insurance increases risk increasing inputs as it protects against additional risk allowing fishers to expand production without taking on greater risk.

Proposition 3.1 also provides new insights into how the selection of an index and its interaction with fisher risk leads to different behavioral responses in fishers. When both shocks are uncorrelated, the insurance only protects against one of the risks. Fishers mitigate ω risk through risk decreasing inputs, thus they will decrease input use when insurance is structured on ω. However, fishers will always increase input use when insurance is structured on θ as the concave, risk increasing nature of $\theta f(X)$ will always expand production.

It is likely that the ω and θ are correlated to some extent. For example, strong winds can affect fisher's ability to catch and biological upwelling at the same time. Therefore, we expand the proposition to include perfect correlation between θ and ω as a means to bookend the full range of possible correlations. In this unique case, basis risk is eliminated and insurance would provide protection against all sources of risk.

Proposition 3.2. *For feasible index insurance contracts specified at either trigger, $\bar{\omega} = 0$ or $\bar{\theta} = 0$, when ω and θ are perfectly correlated random variables, the change in the optimal input is ambiguous when $h_x(x) < 0$ and increases when $h_x(x) > 0$.*

Proof. Perfect correlation implies $\theta < 0$ when $\omega < 0$ and $\theta > 0$ when $\omega > 0$ since both distributions have mean zero, $\mathbb{E}[\theta] \equiv \mathbb{E}[\omega] = 0$. The bounds of the integral can be with respect to either trigger. For simplicity, we will use $\bar{\omega}$ as the trigger, but the proof holds with $\bar{\theta}$.

$$\begin{aligned}\frac{U}{\partial x \partial \gamma} = &\int_{-\infty}^{\bar{\omega}} \int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) + (1-J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(1-J(\bar{\omega})) d\omega d\theta \\ &+ \int_{\bar{\omega}}^{\infty} \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(-J(\bar{\omega})) d\omega d\theta\end{aligned} \tag{10}$$

Suppose insurance fully covers the loss between states, then utility in the good state and bad state are equal to each other so that we can factor out like terms in Equation 10.

$$\begin{aligned}\frac{U}{\partial x \partial \gamma} = &u''(\cdot) J(\bar{\omega})(1-J(\bar{\omega})) \\ &\times \left[\int_{-\infty}^{\bar{\omega}} \int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega d\theta - \int_{\bar{\omega}}^{\infty} \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega d\theta \right]\end{aligned} \tag{11}$$

By Lemma 3.2, when $h_x(X) < 0$ the interior is ambiguous so Equation 11 cannot not be signed, but is unambiguously positive when $h_x(X) > 0$. □

Proposition 3.2 shows there is a tension between risk reduction and profit when stock risks are correlated with extraction risks. Insurance replaces the variance reduction benefits of risk decreasing inputs, which incentivizes less use. However, less input use will also lead to lower harvest. Fishers decide whether the relative loss in income for lower variance is worthwhile. When θ and ω are perfectly correlated with each other, insurance covers stock as well as extraction risk. Mitigating stock risk through the insurance contract encourages fishers to expand production as insurance compensates some of the additional increasing risk of $\theta f(X)$. Whether fishers reduce or increase harvest depends on the effect of many factors such as how risk increasing or decreasing the input is, the degree of risk aversion, and the relative magnitude of the variances.

4 Insurance with multiple inputs

The single input model provides clear, testable insights. However, real world fisheries are more complex than single input models. We develop a multi-input model to represent this complexity. The multi-input model provides the foundation of our numerical analysis that leverages parameter estimations from Asche *et al.* (2020). Their study estimated production and risk effect parameters across three inputs in Norwegian fisheries. The numerical analysis will allow us to clarify the directional effects of insurance on fisher behavior for valuable Norwegian fisheries.

We extend the model of the previous section to two inputs, $X \in \{x_a, x_b\}$. Two inputs sufficiently articulate the complexities that arise while still remaining tractable to solve.

There are two additional effects to consider when adding more inputs. The interaction between inputs leads to the first effect. Changes in input use may not correspond to the direction dictated by their respective extraction risk effects. For example, a fisher may not choose to reduce a risk decreasing input if the cross partial effects of production and risk negatively impact production of another input. We summarize the conditions that lead to unequivocal changes in input use in Proposition 4.1. We only focus on uncorrelated shocks because Proposition 3.2 demonstrates correlated shocks are already difficult to sign due to the tensions between stock and extraction risk effects for single inputs.

Proposition 4.1. *In fisheries with two inputs, when θ and ω are uncorrelated, index insurance will change the optimal use of a specific input in the direction of an input's own risk effect when the following sufficient condition is true:*

$\frac{\partial U}{\partial x_a \partial x_b} > 0$ *when both inputs share the same risk effects, and* $\frac{\partial U}{\partial x_a \partial x_b} < 0$ *when inputs have opposite risk effects.*

Otherwise, Index Insurance will have ambiguous effects on optimal input choice.

The proof is included in Section A.3.

The second effect is a straightforward consequence of adding inputs. Total change in harvest is controlled by the relative change in inputs from insurance and each inputs' marginal productivity.

Proposition 4.2. *When index insurance leads to increases (decreases) of both inputs, total harvest will increase (decrease).*

Otherwise, total change in harvest depends on the relative change in input use and $\frac{\partial f(x_m)}{\partial x_m}$

Proof. The total derivative of expected harvest is:

$$\frac{d\mathbb{E}[y]}{dx} = \hat{B}\frac{\partial f(x_a, x_b)}{\partial x_a}dx_a + \hat{B}\frac{\partial f(x_a, x_b)}{\partial x_b}dx_b \tag{12}$$

Marginal production is concave, therefore $\frac{\partial f(x_m)}{\partial x_m} > 0$. When $dx_a > 0$ and $dx_b > 0$, Equation 12 is always positive. The opposite is true when $dx_a < 0$ and $dx_b < 0$.

For inputs with changes in opposite directions, Equation 12 is positive or negative contingent on the relative weight between $\frac{\partial f(x_a)}{\partial x_a}dx_a$ and $\frac{\partial f(x_b)}{\partial x_b}dx_b$ □

Proposition 4.2 indicates that reductions in inputs that are overridden by subsequent increases in more productive inputs will limit the conservation potential of index insurance. Just because insurance lowers one margin of production does not mean it will lead to less total harvest.

These two insights will help explain the modeled responses of fishers in Section 5. In general, stock and extraction risk effects remain the leading influences on guiding fishers input choices after buying insurance. Proposition 4.2 and Proposition 4.1 identify that within the complicated nexus of multiple input interactions, certain inputs may dominate the overall outcomes. Both propositions indicate that inputs that share risk effects e.g. all inputs are risk increasing, ought to have the same conclusions as observed in Section 3. Fisheries that use inputs with opposite risk effects are impossible to sign without further information. We turn to simulations in the following section to elucidate the ambiguity.

5 Numerical Simulations

We use numerical simulation to better understand how correlation between the random variables leads to ambiguity, and to determine the magnitude of change in input use for Norwegian fisheries using the parameters found in Asche *et al.* (2020). Monte Carlo simulations find expected utility across 1000 random draws of stock and extraction shocks. A comprehensive set of parameters test the sensitivity of fisher input choices with index insurance. All simulations are conducted in R with accompanying code available at [WILL ADD ONCE REPO IS CLEANED].

5.1 Simulations with one input

We use the structural form where $f(x) = x^\alpha$ and $h(x) = x^\beta$ to most easily integrate risk increasing or decreasing effects in $h(x)$ (Equation 13).

$$\pi = x^\alpha(\hat{\beta} + \theta) + \omega x^\beta - cx^2 \tag{13}$$

Mean production $f(x)$ is concave so that $\alpha > 0$. Extraction risk effects on the input can either be risk increasing or decreasing with $\beta \lesseqgtr 0$. We apply convex costs, $c(x) = cx^2$, for smoother convergence in the maximization procedure. Stock and extraction shocks are normally distributed with $\theta \sim N(0, \sigma_\theta)$ and $\omega \sim N(0, \sigma_\omega)$. The shocks are linked through a copula with correlations ranging from $[0, 1]$.

Fishers will choose inputs x to maximize expected utility with an exogenous insurance contract. Constant Absolute Risk Aversion (CARA) utility is used to better account for negative shocks and profit loss. We examine insurance built on ω first to test the more ambiguous cases (Equation 14).

$$
\begin{aligned}
U \equiv \max_x \mathbb{E}[u] &= \mathbb{E}[(1 - \exp(-a(\pi(x, \hat{\beta}, \theta, \omega) + \mathbb{I}(\gamma))] \\
\mathbb{I}(\gamma) &= \begin{cases} -\rho\gamma & \text{if } \omega \geq \bar{\omega} \\ (1-\rho)\gamma & \text{if } \omega < \bar{\omega} \end{cases}
\end{aligned} \tag{14}
$$

We convert γ to be a percentage of mean optimal profit without insurance for interpretability. For example, $\gamma = 1$ would represent a payout equivalent to expected profit before insurance, and $\gamma = 0$ represents no insurance. The insurance contract is triggered by $\omega < \bar{\omega}$.

We create a wide parameter space to assess the sensitivity of optimal input choices to different model parameters. We vary the relative productivity of the input $\alpha \in \{0.25, 0.5, 0.75\}$, the extraction risk effect of the input $\beta \in \{-0.7, -0.5, -0.3, -0.1, 0.1, 0.3, 0.5, 0.7\}$, the risk aversion parameter $a \in \{1, 2, 3\}$, the stock shock variance $\sigma_\theta \in \{0.1, 0.2, 0.3, 0.4\}$, the extraction shock variance $\sigma_\omega \in \{0.1, 0.2, 0.3, 0.4\}$, and the correlation between the shocks ranging from 0 to 1 with 0.2 steps.

First we iterate γ from 0 to 1.5 to show the change in optimal input use for a single input. Selected parameters for Figure 1 are for demonstration purposes. The full parameter space is explored in the accompanying code.

Optimal input use changes monotonically with index insurance depending on the risk characteristics of the input (Figure 1). The direction of all input changes follows expected theory. The bottom right panel shows the new instance where a risk decreasing monotonically increases when the shocks are correlated following Proposition 3.2.

The concavity of utility, as demonstrated by the blue parabolas in all panels of Figure 1, implies there exists an optimal amount of insurance for fishers to buy. The monotoncity of input use in all cases suggests that the insurance level that maximizes utility will preserve the sign of input changes. Therefore, an endogenous choice of insurance will not affect the direction of input change, but it will affect the magnitude.

For example, risk increasing inputs have higher levels of insurance payouts that maximize utility. Allowing fishers to choose insurance coverage ensures that the choice of insurance and input use changes are welfare improving and will not bias input choices with over or under

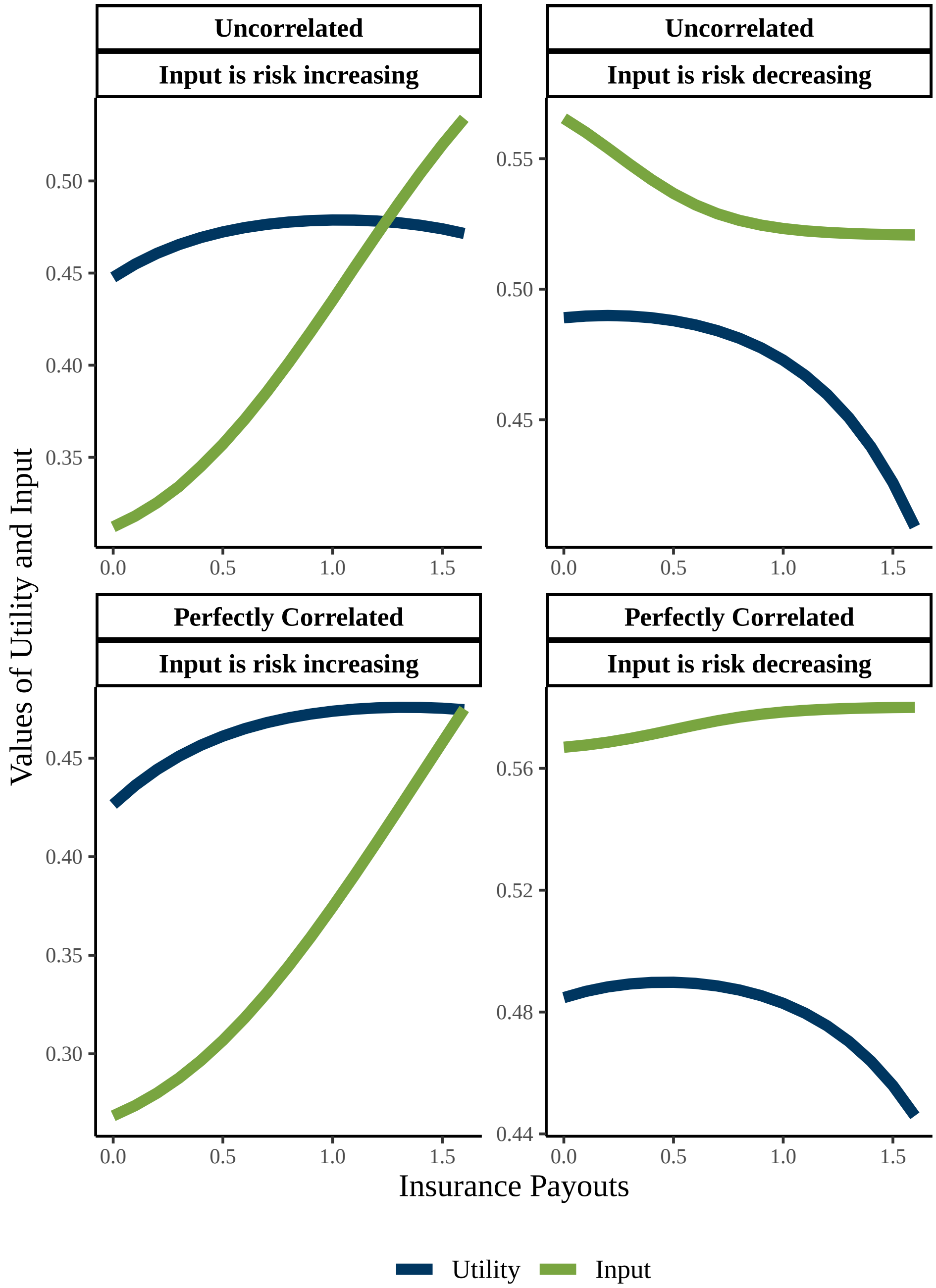

Figure 1: Improvements in utility (green lines) and changes in optimal input use (blue lines) with index insurance. Shocks are uncorrelated with high mean productivity ($\alpha = 0.75$), high risk aversion $a = 3$, and relatively more variable weather shocks than biological ($\sigma_w = 0.4$ vs $\sigma_t = 0.1$)

investment of insurance. Simulations moving forward will allow fishers to choose both inputs and insurance coverage.

Adding an endogenous γ to Equation 14 amends the choice set in Equation 15. Furthermore, we run two groups of simulations. One with the insurance contracted indemnified on ω as shown in Equation 14, and another with the index built on θ to test all conditions of Proposition 3.1 and Proposition 3.2.

$$
\begin{aligned}
U \equiv \max_{x,\gamma} \mathbb{E}[u] &= \mathbb{E}[(1-\exp(-a(\pi(x,\hat{\beta},\theta,\omega)+\mathbb{I}(\gamma))] \\
\mathbb{I}(\gamma) &= \begin{cases} -\rho\gamma & \text{if } \omega \geq \bar{\omega} \\ (1-\rho)\gamma & \text{if } \omega < \bar{\omega} \end{cases}
\end{aligned}
\tag{15}
$$

Correlation between stock and extraction risk impact optimal choice of input in line with Proposition 3.1 and Proposition 3.2 when contracts use ω as the index. The clusters of bar graphs furthest to the left along the x-axis in each panel are changes in input use when shcoks are uncorrelated (Figure 2). Uncorrelated shocks have consistent signs of input use in accordance to the underlying inputs risk effect function. The bars in red indicate the input is risk decreasing, while the blue bars are risk increasing. The stronger the risk effect, the more pronounced the change in input use. All risk decreasing inputs had lower input use when shocks are uncorrelated while all risk increasing inputs saw higher use.

The productivity of inputs strongly influences the change in input use particularly for risk decreasing inputs. When inputs are relatively less productive (left panel, $\alpha = 0.25$), fishers are more willing to reduce the unproductive input in favor of the protection offered by insurance. They lose less in production while gaining more variance reduction by substituing with insurance. As productivity increases, fishers would prefer to keep extracting at more efficient levels than reduce input use. This tension is the primary driver towards higher risk decreasing input use when the shocks become correlated.

Perfectly correlated shocks, shown by the far right cluster of bars in each panel, show that risk increasing inputs will always see more use, while risk decreasing inputs use could be lower or higher depending on the relative productivity. The tradeoff between the risk reducing capacity of the inputs and its marginal productivity drives this result. Because the variables are perfectly correlated, insurance protects against both stock and extraction risk. Insurance decreases the need to reduce extraction risk through $h(x)$, but increases the desire to take on more stock risk to achieve greater harvests. Which of these effects dominates depends on how productive is the input. Inputs with low productivity do not provide as much benefit when taking on further biological risk, so fishers will decrease their use if the input is risk decreasing. Very productive inputs provide excellent marginal returns and it becomes worthwhile to pursue additional harvest as insurance protects the additional risk.

The more correlated the variables, the stronger the effect. The interior cluster of bars in each panel show cases where the shocks are partially correlated. Perfectly correlated indices imply zero basis risk and would be considered "perfect" contracts. The behavioral implications of our model suggest that this form of basis risk could lead to more conservation degradation than imperfect uncorrelated contracts. However, basis risk is a significant impediment to insurance uptake (Binswanger-Mkhize 2012; Clarke 2016). Within our simulations, the average improvement in utility for contracts with high basis risk was 1.5%, and 7.8% for "perfect" contracts implying that fisher demand would be much higher for the perfect contract. If policymakers want to promote well designed contracts, there must be other considerations to curtail harvest expansion otherwise long run sustainability will be impeded.

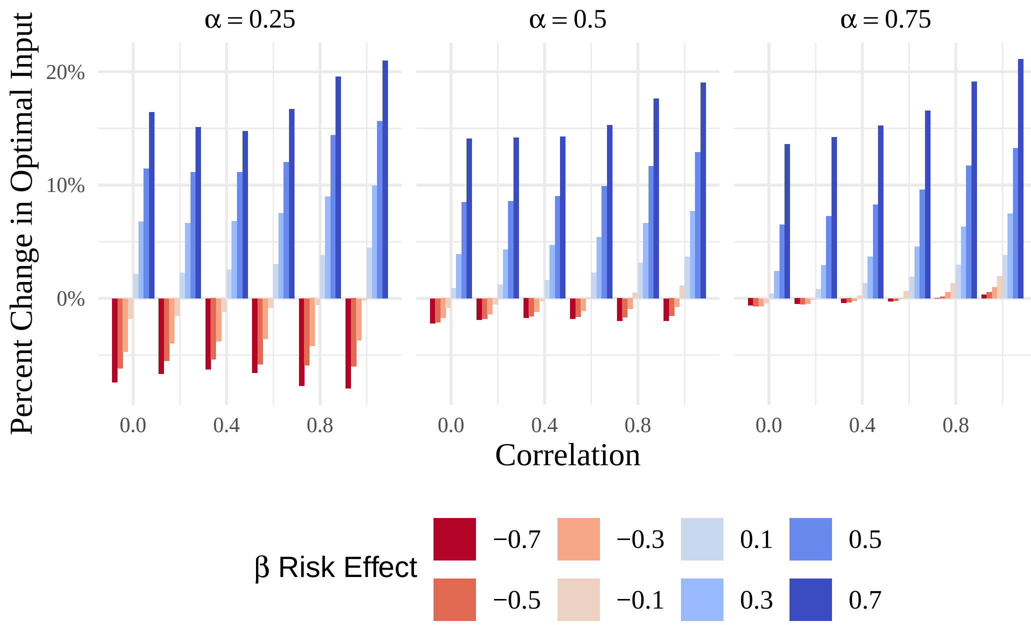

Figure 2: Percentage change in optimal input with an index insurance contract using extraction risk, ω, as the index. Risk increasing inputs (blue bars) always increase input use, while risk decreasing inputs (red bars) have ambiguous effects depending on the basis risk (correlation on the x-axis) and relative stock productivity of the input (α in the panels).

Figure 3 verifies the remaining properties of Proposition 3.1 and Proposition 3.2. Contracts built on θ as the index show more bias towards overfishing because of the inherent risk increasing characteristics of $f(x)$. Uncorrelated shocks imply that insurance will only protect shocks on θ. Production can expand as insurance protects the additional risk of $\theta f(x)$ regardless of the risk decreasing inputs. The results become ambiguous when the shocks are correlated for the same reasons as when contracts are built on ω. The overall protection offered by insurance will allow whichever marginal effect between $h_x(x)$ and $f_x(x)$ to dominate the direction of optimal input use.

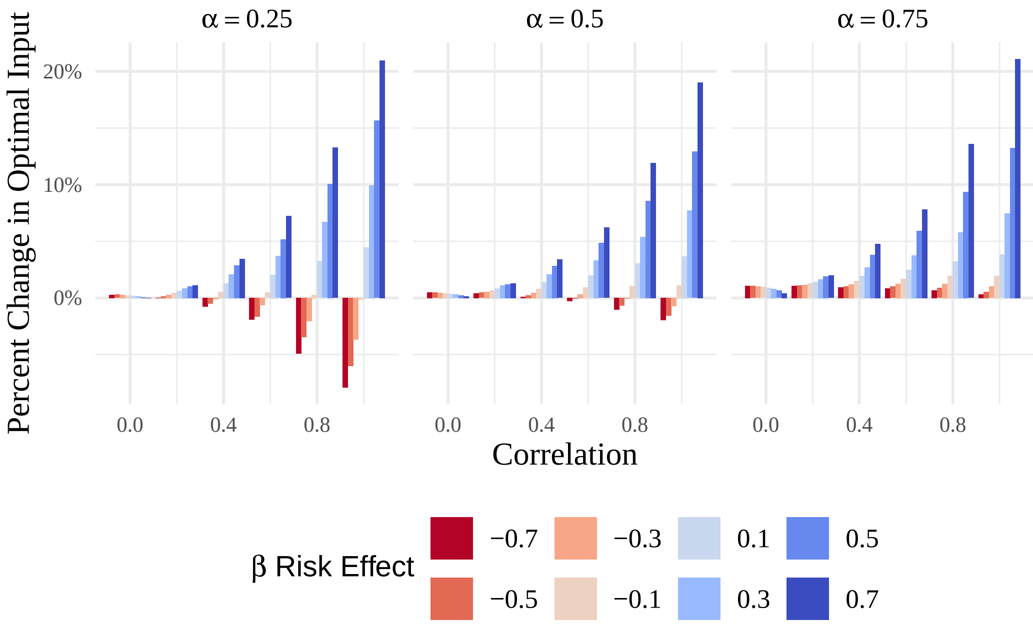

Figure 3: Percentage change in optimal input with an index insurance contract indenmified on stock risk, θ. Higher corrleations (x-axis) lead to amiguous results where ω risk decreasing inputs (red bars) could lead to decreases in input use. Panels indicate the stock production elasticity. Risk increasing inputs (blue bars) always lead to greater input use.

Magnitude of input changes are sensitive to other parameters. More risk averse fishers respond more aggressively to insurance and make relatively more changes toward their input decisions (Panel A in Figure 4). Risk aversion implies more sensitivity towards risk. The protection from insurance has greater marginal value for more risk averse fishers. Greater marginal value of insurance means they can invest less into risk reducing inputs than before, and have more protection from greater shocks with risk increasing inputs.

Fisher input choice are much more responsive to insurance protection from larger productivity risks (Panel B Figure 4). Similar to risk aversion, the greater the shocks the greater the marginal value of insurance is to mitigate those shocks. In more volatile environments, insurance provides significantly more income smoothing leading to similar incentives as the higher risk aversion example.

Trigger levels do not appear to have differing impacts on input use. Setting the trigger levels to more catastrophic coverage did not encourage fishers to change their input use relative to the other parameters. While necessary for applying Lemma 3.1 and Lemma 3.2 in the proofs, the results of Proposition 3.1 and Proposition 3.2 would appear to hold if $\bar{\omega} \neq 0$ and $\bar{\theta} \neq 0$.

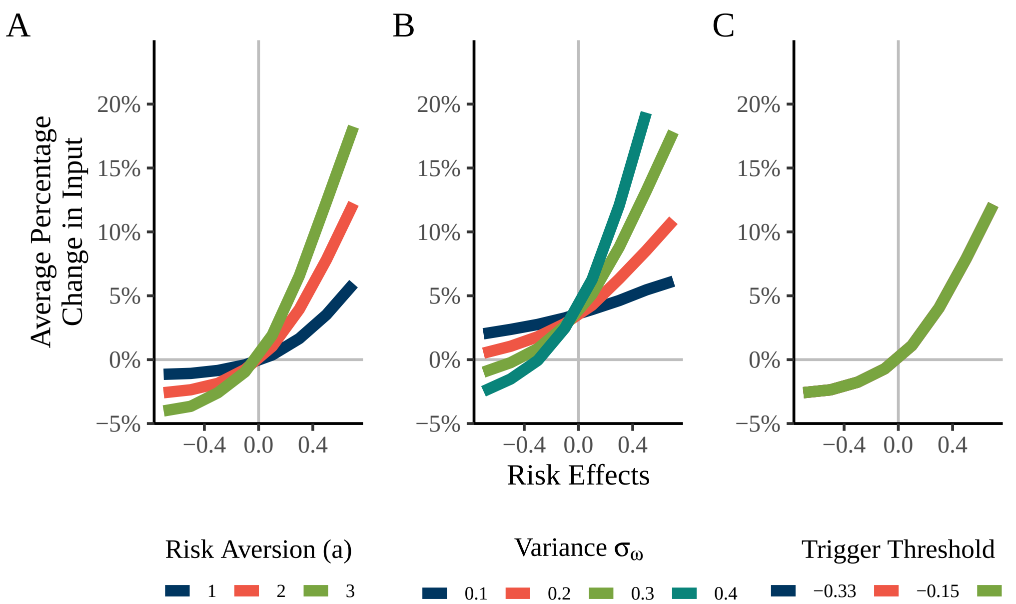

Figure 4: Risk Aversion (A), weather variance ω (B), and trigger (C) all influence the magnitude of change in harvest. Mean production elasticity is set to 0.5. Average percent change in input (y-axis) is summarized across all other parameter combinations for each risk effect value of β.

In the next section we use parameters from Asche *et al.* (2020) to calculate the overall change in harvest with multiple inputs interacting with index insurance.

5.2 Application to Norwegian Fisheries

Fishery extraction risk effects are rarely estimated, though appear crucial to determining the magntiude of input change with index insurance. The only known study to date that calculates risk effects is that of Asche *et al.* (2020). They used a non-linear estimator to calculate the production and risk parameters of a Just-Pope function across four different vessel types. We will use their coefficient calculations to calibrate an estimate of the magnitude of input and harvest change that index insurance would incentivize if offered to important Norwegian fisheries.

Asche et al., (2020) aggregated by vessel type and not species, so there is no reasonable estimate for biomass. They accounted for biomass using fixed effects in their regression, but without additional information we cannot parameterize the mean and variance of biomass. Therefore, our simulations normalize mean biomass to 1 and we assume the stock shocks, θ, have three degrees of correlation with ω, $\{0, 0.5, 1\}$. Norwegian fisheries are well managed so the stock variance could be mitigated through quota systems or accurate stock assessments. The simulation model uses three inputs (capital k, labor l, and fuel f) instead of one (Equation 16).

$$\pi(k,l,f) = k^{\alpha_k} l^{\alpha_l} f^{\alpha_f}(\widehat{\beta} + \theta) + \omega k^{\beta_k} l^{\beta_l} k^{\beta_f} - c_k k^2 - c_l l^2 - c_f f^2 \tag{16}$$

Mean production, α, and risk, β, elasticities control the stock and extraction risk effects respectively. Each parameter is indexed to a particular input through the subscript, e.g. fuel mean production elasticity is α_f. Fishers in the simulation choose inputs and insurance coverage to maximize expected utility. We show their choice based on a ω contract (Equation 17), but also run a model specification with a contract built on θ.

$$\begin{aligned} U \equiv \max_{\gamma,k,l,f} \mathbb{E}[u] &= \mathbb{E}[u(k^{\alpha_k} l^{\alpha_l} f^{\alpha_f}(\widehat{\beta} + \theta) + \omega k^{\beta_k} l^{\beta_l} k^{\beta_f} - c_k k^2 - c_l l^2 - c_f f^2 + \mathbb{I}(\gamma)] \\ \mathbb{I}(\gamma) &= \begin{cases} -\rho\gamma & \text{if } \omega \geq \bar{\omega} \\ (1-\rho)\omega & \text{if } \omega < \bar{\omega} \end{cases} \end{aligned} \tag{17}$$

Table 1 shows the production and risk elasticities of the four vessel types used in the simulation. While not all elasticities were found to be statistically different from zero, we used their raw values because dropping only those variables that are significant in both matching parameters would have kept only a few valid combinations. All non-significant elasticities led to small changes, but their interactions with other inputs could partially drive some of the observed outcomes.

Table 1: Production and Risk elasticities of Norwegian Fisheries from Asche et al., (2020)

	α_k	α_l	α_f	β_k	β_l	β_f
Coastal Seiners	0.294	0.421	0.457	0.184	-0.432	0.119
Coastal Groundfish	0.463	0.421	0.355	0.965	-0.080	0.113
Purse Seiners	0.941	-0.108	0.605	-0.454	-0.231	0.160
Groundfish Trawlers	0.210	0.106	0.531	-2.788	-0.110	-0.024

We use the same parameter space as the previous simulations to test the sensitivity of fisher input choices with index insurance. We plot the distribution of input change after insurance for all uncorrelated combination of parameters in Figure 5 based on a contract with ω as the index. Figure 5 also allow us to examine whether the conditions of Proposition 4.1 hold with real world combinations[3]. We report the highest density as an indicator of the general direction of input change.

Most changes in inputs tend to change in the direction expected of their own individual risk effects. For example, fuel and capital are risk increasing inputs for Coastal Seiners while labor is risk decreasing. In the top left panel of Figure 5 the distribution of the percent change in use for the risk increasing inputs (capital in green and fuel in green) were always positive, and negative for the risk decreasing input (labor in green). Despite the mix, each input follows their respective input and demonstrates the conditions of Proposition 4.1 can hold. The Groundfish Trawler fishery also shows that the conditions of Proposition 4.1 hold. All inputs are risk decreasing. The distribution of change in inputs in the bottom right panel are negative.

The conditions of Proposition 4.1 do not hold in the case of the Purse Seiner and Coastal Groundfish fisheries. The Purse Seiner fishery never used labor due to the negative production elasticity. Capital and fuel both saw positive and negative changes to their input use despite capital being risk decreasing and fuel being risk increasing. While there is no consistent pattern for what leads the reversal in directions, it appears that when θ variance is high captial tends to dominate fuel risk so that the fisher choose less capital and fuel. Higher ω variance tends to lead fuel and capital to both increase.

Labor in the Coastal Groundfish fishery is risk decreasing, yet always saw an increase in the simulations. The risk parameter of labor is relatively small compared to the risk increasing coefficients of capital and fuel. The cross partial mix of the inputs may explain why fishers add more labor. As insurance strongly incentivizes capital and fuel increases, labor must also increase to further enhance those other inputs.

Input changes lead to harvest changes. We examine the total change in harvest for all parameters in Figure 6 for a contract triggered on ω. Overall, insurance leads to relatively small

[3]Proposition 4.1 requires shocks to be uncorrelated otherwise ambiguity enters. Figure A1 in the appendix shows the same results with the entire correlation parameter set. The change in direction for each input becomes much more ambiguous as expected based on the results of Proposition 3.2

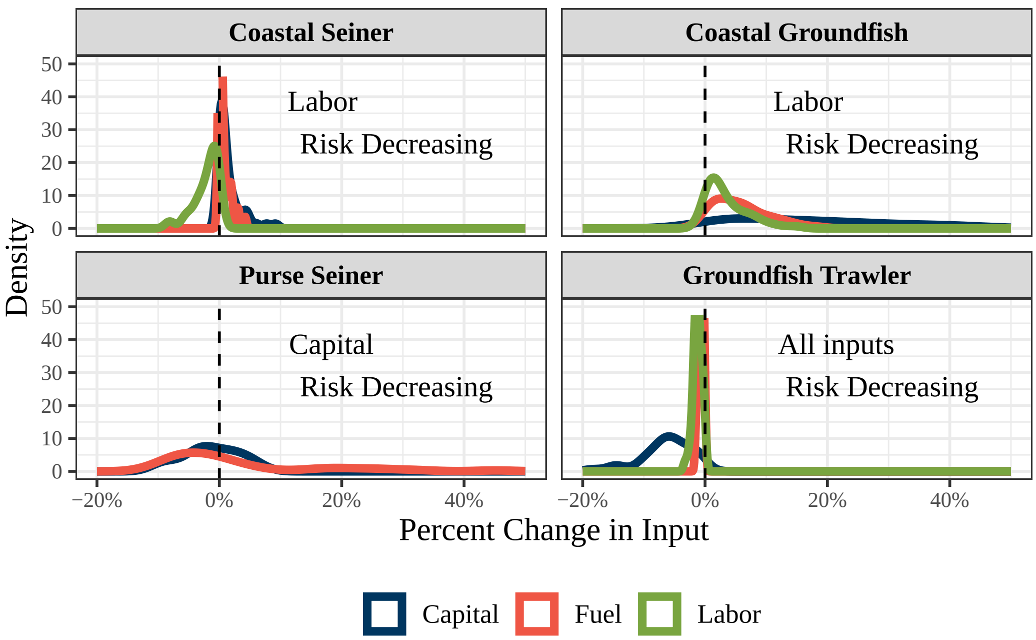

Figure 5: Density plots of the percent change in input use for each vessel type in Norwegian fisheries. The dashed black line represents no change in input use. Risk decreasing inputs are labeled. Labor (green lines) is dropped for Purse Seiners because labor was never used in simulations due to negative productivity elasticity. Correlation between shocks is set to 0 in order to test the conditions of Proposition 4.1

changes in harvest for all fisheries, but increases are stronger than decreases. Coastal Groundfish see the largest and most consistent increase in harvest. Median harvest increased by 12.5% with a max increase of 50%. Coastal Groundfish have the most risk increasing inputs out of the estimated fisheries and always saw increases in input use (Figure 5).

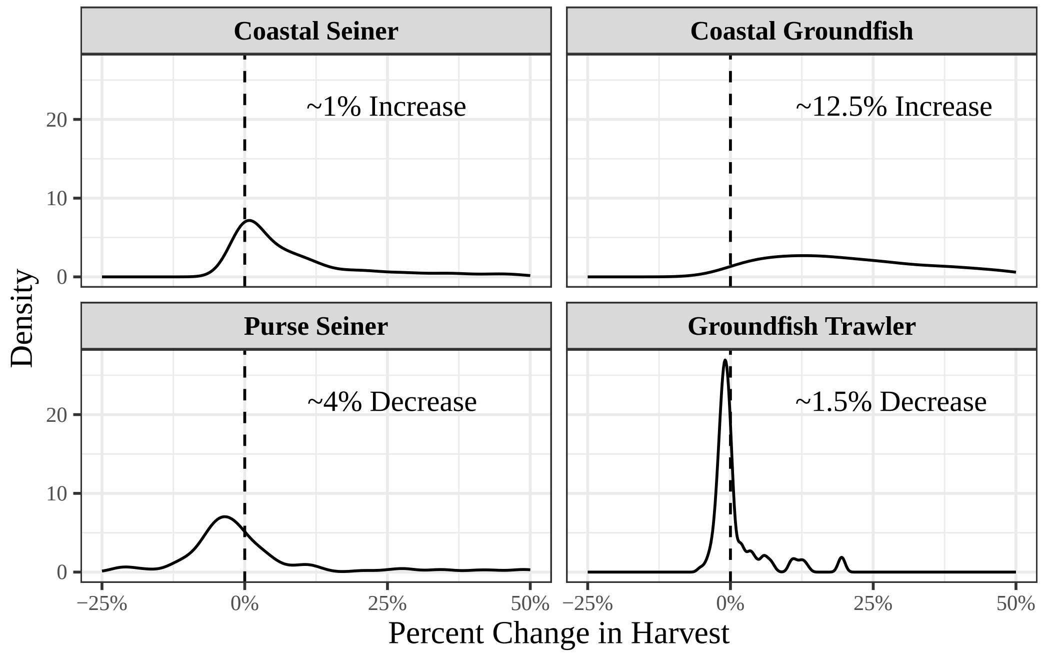

Figure 6: Density plots of the percent change in harvest for each vessel type in Norwegian fisheries. The dashed line represents no change in harvest. The text labels represent the median percent change in harvest for each vessel type.

Coastal Seiners had a relatively balanced spectrum of risk effects. The input mix in this case led to both increases and decreases in input use, which on net led to near zero changes in harvest. There is a slight skew towards increased harvest, but drastically less than the Coastal Groundfish fishery.

Deep water fleets generally saw reductions in harvest. Purse Seiners tended to decrease harvest by 4%. Groundfish trawlers consistently see small decreases of 1.5% in harvest (Figure 6). All inputs are risk decreasing with capital having the strongest risk effect out of all inputs across all fisheries. However, it has a relatively low marginal productivity. Insurance decreases trawler capital use by about 8%, but the low productivity leads to only a 1.5% decrease in overall harvest.

Applying an insurance contract indemnified on θ instead of ω shows similar results, but shifts the direction towards more overfishing (Figure 7). The most prominent shifts occur in the Groundfish Trawlers and Coastal Seiner fleets. In Figure 6, the percent change in harvest for Coastal Seiners is indistinguishable from zero. With a θ index contract, there is now a pronounced shift towards overharvesting (Figure 7).

Groundfish Trawlers have opposite results with a contract indemnified on θ. Despite the risk decreasing dominance of capital, fishers will choose to increase production as insurance drastically protects against the added harvest risk. This result most clearly shows the impact of different insurance contracts and the potential for maladatpive behavior change. Without considering all the margins for change, insurance protecting against biological risk will still encourage overfishing without additional constraints.

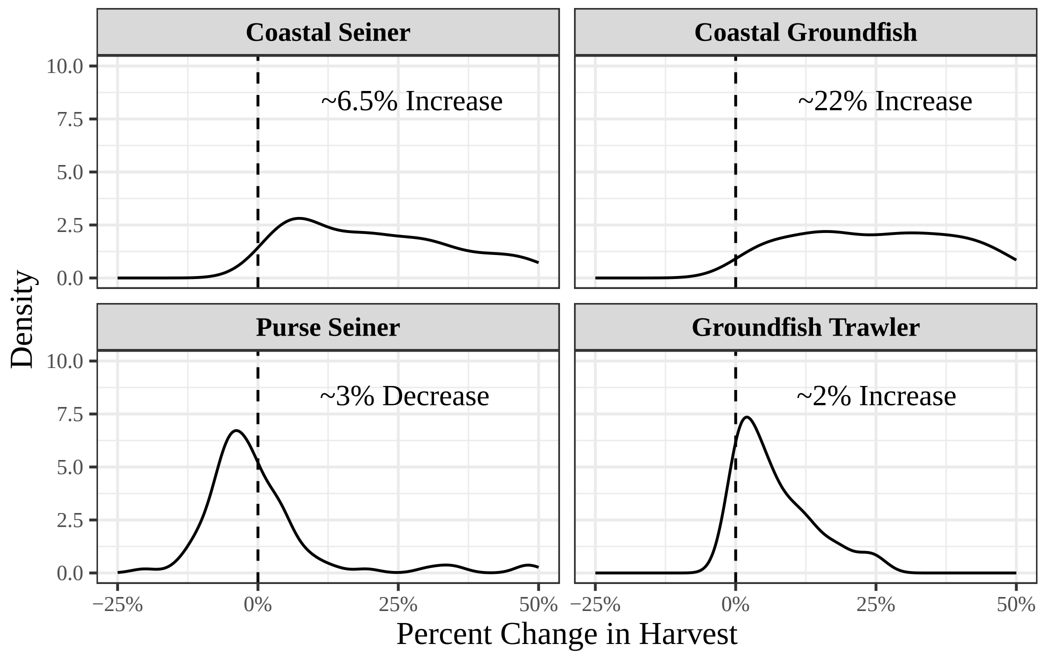

Figure 7: Density plots of the percent change in harvest for each vessel type in Norwegian fisheries with insurance contract indemnified on biological risk θ. The dashed line represents no change in harvest. The text labels represent the median percent change in harvest for each vessel type.

6 Discussion

This paper makes three distinct contributions. First, index insurance will have behavioral impacts on fishers' input decisions, which in turn will lead to changes in fishery sustainability. Second, the design of index insurance contracts affects policyholder behavior contingent on the mitigation strategies available to protect the underwritten risk. Third, fishers face distinct sources of risk through the biology of fish stocks and inherent harvesting variability that can be modeled with a new stochastic production function.

The fundamental driver of fishers' behavior changes is whether the marginal change in productivity is balanced by the marginal change in risk. Fishers are more willing to increase production if insurance negates the additional risk of expanded production. Since insurance lowers risk, fishers need less self insurance through risk reducing inputs and can reduce their overall input use. However, using less inputs implies less catch and revenue creating a unique tension that exists throughout the analysis. Across all simulations, decreased input use was smaller than increased input use holding all other parameters constant. Behavior change in fisheries will lean towards expanding production creating a dilemma for conservation efforts.

Index insurance would improve welfare in Norwegian fisheries, but also lead to changes in harvest that depends on the extraction risk effects of fishing fleets. Coastal groundfish trawlers increased fishing pressures by 12.5% when offered insurance. Capital and fuel are risk increasing inputs, and encourage the increased harvest. If an insurance policy was applied to provide the income smoothing benefit of insurance, the policymaker must take measures to mitigate the preserve incentive to expand fishing production. Otherwise, the long term health of the stock could be degraded and fishers would be worse off in the long run (Müller *et al.* 2017; John *et al.* 2019; Bulte and Haagsma 2021).

Norwegian pelagic groundfish trawlers would have the opposite considerations. When offered insurance they reduced their harvest by 1.5%. Though small, it will lead to improved fishery sustainability. The long term benefit of insurance would increase with improved stock health. The decline in harvest was driven by a reduction in overcapitalization, because capital was a significantly risk decreasing input. Policymakers should attempt to identify fisheries with risk decreasing inputs for insurance contracts to improve sustainability if index insurance is to operate in isolation of other policies.

Ex-ante identification of input risk effects is challenging. Extraction risk effects remain an elusive concept in fisheries, and need to reconciled in order to articulate more accurate behavior changes of fishery index insurance. Crop covers and pesticide provide clear examples of risk decreasing inputs in agriculture, but what do risk decreasing inputs look like in fisheries? Asche *et al.* (2020) provide empirical evidence of the existence of risk decreasing inputs, but do not elaborate on why or how labor and capital directly decrease risk. Labor is perhaps the more intuitive risk decreasing input. Technical expertise of crew and captains can hedge against luck when fishing (Alvarez *et al.* 2006). Better trained crew can deploy gear in a safe and timely manner, increasing the likelihood of effective sets.

Fuel as a risk increasing input in fisheries makes intuitive sense as well. Fuel is used to power vessels and is a direct cost of fishing. Fishers explore productive fishing grounds for the best location. Every hour at sea increases the harvest reward, but also the chances of failure.

Capital is a more complex input, because it is shown to be both risk increasing and decreasing. Capital in fisheries typically refer to vessel tonnage, engine power, and gear technology. Greater capital increases risk because it allows fishers to explore more fishing grounds, use more efficient gear, and fish in more adverse weather conditions. Alternatively, having larger vessels may be a risk reducing input when common pool resources incentivize the race to fish, as the sooner a fisher harvests from the stock, they assure their income at the expense of other fishers. Adding risk aversion to standard models of common pool fisheries suggests fishers should lower their capital use compared to risk neutral allocations (Mesterton-Gibbons 1993; Tilman *et al.* 2018). Yet, overcapitalization and overfishing are more often observed in the real world. Either fishers are never risk averse or the risk effects of capital are not as simple as the standard model suggests. When capital is allowed to be risk decreasing, optimal input choices are much higher than risk neutral equilibrium suggesting fishers are making rational, risk averse decisions even while overfishing.

Fishers exposure to multiple sources of risk further necessitates insurance, but also makes it more challenging to design. Proposition 3.2 shows the interaction between the stock and extraction risk obscure the moral hazard of insurance. It is far mor elikely that weather variables will have some degree of correlation. The assumed volatility of more fish in the ocean leads the harvest function to implicitly be risk increasing in our specification of stochastic production. With this assumption, designing a contract around a stock shock will bias the results towards more overfishing. In the Norwegian fisheries, contracts built on stock risk increased median fish harvest in all fisheries. However, the leading candidates for possible indices in fisheries index insurance are currently weather variables most often associated with biological stock risks (Watson *et al.* 2023). Designing contracts solely on these variables may lead to harvest increases that run contrary to conservation goals.

However, most bioeconomic models simplify the complex effects of stock dynamics into multiplicative forms as modeled in this paper. Instead, different forms of risk could be embedded into the biological component of fishery models. Stock variance could be greater in overfished stocks instead of healthier ones, reflecting more vulnerability in weaker states (Sims *et al.* 2018). Adapting alternative, more biologically focused specifications of stock risk could change the behavioral effects of insurance. Fishers may be more willing to expose themselves to greater risk at more vulnerable stock levels with insurance. Alternatively, insurance could help mitigate risk and incentivize fishers to move toward healthier stocks with less variance by alleviating income pressures to fish. Further analysis is required to understand the full implications of stock risk effects in fisheries.

The transfer between inputs and insurance reflects the substitution between self-insurance and formal insurance (Quaas and Baumgärtner 2008). If index insurance is designed to reduce fishing capacity, efforts must be made to ensure that it does not take away from the self resiliency of fishers. Labor appears to be consistently risk reducing and acts as a form of self insurance. If index insurance incentivizes captains to hire less crew, the stock of fish may be preserved, but less employment may reverberate throughout the community. Fishing is often a primary employment opportunity in coastal communities. The resiliency of the community would be compromised rather than enhanced with fewer jobs. The same idea applies to capital. If fishers are over investing in capital to hedge against some form of risk, policymakers need to be sure the insurance is replacing maladaptive self insurance behavior.

The primary form of self insurance in fisheries is management. To this point our analysis explicitly modeled scenarios without the existence of management. We wanted to analyze the interaction of insurance on fisher behavior in unconstrained settings first to derive a clearer incentive structure. Most fisheries are managed in some form. The interaction between management and insurance may be complementary or substitutes. For example, well managed fisheries that have responsive harvest control rules may not need insurance. The management system is already providing the necessary risk protection. Insurance demand and uptake may be low in these fisheries. Insurance could instead complement management to provide the financial relief that management cannot offer. Managers often focus on the biological health of the fishery that can run at odds with fishers' desires to enhance their income. Insurance can act as the financial relief and allow managers to pursue more active strategies to protect fish stocks without political resistance from lowered quotas. Additionally, management can provide the constraints on insurance moral hazard so the income smoothing benefits are passed to fishers, but not the long term degradation. The interaction between insurance and management requires further investigation especially with the the numerous management strategies that exist in fisheries.

Design and access of insurance must also consider equity. The current US federal disaster relief program is inequitable with bias towards large industrial vessels (Jardine *et al.* 2020). Creating another program with equal inequity would be foolhardy. Current US farm subsidies, including insurance premiums, are heavily skewed towards large agribusinesses (White and Hoppe 2012). Dimensions of access, procedural, representation, and distribution must all be built into the design of new fishery index insurance programs (Fisher *et al.* 2019). For example, small scale fishers may have income constraints that prevent them from buying the initial contract. Micro-finance options connected to insurance have been used in agriculture to alleviate this burden with some success (Dougherty *et al.* 2021). Additionally, who receives the payouts needs thorough consideration. Payouts solely to vessel owners may ignore support to valuable, yet vulnerable fishery participants. Deckhands and crew are laid off during closures. If index insurance payouts are going through the entire fishery, the most vulnerable in the event of closures must be protected as well. Contract stipulations could mandate that only cost expenses are covered by payouts thereby including lost wages to the crew. Agriculture contracts often are designed to directly cover expenses (He *et al.* 2020). Labor expenses could be included in the contract to ensure that the crew is protected as well.

Our model only directly models behavior change through moral hazards. Index insurance could be designed to incentivize other forms of sustainable behavior change. We define three pathways insurance can change behavior: Moral hazards, Quid Pro Quo, and Collective Action. Moral hazards were proven in this paper to have ambiguous impacts controlled by the risk characteristics of fishery inputs. The incentives of moral hazards will always exist, therefore other measures could be taken to either limit the downside behavioral effects of insurance or stimulate other forms of sustainable behavior.

Quid Pro Quo expands contract design to explicitly build in conservation measures. Fishers would be required to adopt sustainable practices in order to qualify for insurance. Quid Pro

Quo is already used in agricultural insurance in the form of Good Farm Practices. Farmers must submit management plans to US Risk Management Agency that clearly outline their conservation practices in order to qualify for insurance. Working closely with management agencies, insurance companies could design contracts that require fishers to follow fishery specific management practices. For example, fishers may be incentivized to use more sustainable gear types, have an observer onboard, or reduce bycatch. Management input is needed to tailor fishery best practices to insurance contracts. Further research would need to uncover the full impact of Quid Pro Quo, but an initial hypothesis would be the fishers will be willing to adopt sustainable practices so long as the marginal gain in utility from the insurance is greater or equal to the necessary sustainable changes. Otherwise fishers will not want to buy the contracts and the insurance has no binding stipulations to change the fishery.

Collective action ties insurance premiums to biological outcomes to leverage the political economy of the fishery. Insures could reduce premiums in fisheries that have robust management practices such as adaptive harvest control rules, stock assessments, or marine protected areas in the vicinity. Fishers could either pressure regulators to adopt these actions or form industry groups to undertake the required actions. Insurers would agree to this if triggers are connected to biological health so that negative shocks are less frequent and thus payouts occur less. Fishers gain from the reduced insurance premium and the increased sustainability of harvest with rigorous management in place.

Ultimately, if index insurance is to be used in fisheries, it must be designed with clear objectives and intentions. Index insurance can meet objectives of income stability and risk reduction, but there has been an implicit assumption by practitioners that index insurance will always lead to improved sustainability. Without considering the behavior change of fishers when adopting insurance, the outcomes may not be as expected. New insights derived from this paper will help guide the efficient and sustainable implementation of fisheries index insurance.

A Appendix

A.1 Proof of Lemma 3.1

Lemma 3.1 *Individual fisher expected marginal profit of a specific input, x_m, is greater in the good state than expected marginal profit in the bad state when $h_{x_m}(X) > 0$. Expected marginal profit is higher in the bad state when $h_{x_m}(X) < 0$. If $h_{x_m}(X) = 0$, the marginal profits are equivalent in both states.*

Proof. By the first order conditions, there exist optimal values of any individual input x_m that must be chosen before the realization of the states of the world. Therefore $h(X^*)$, $f(X^*)$, and $c(X^*)$ are equal across states.

First we prove the case for contracts built on ω. The steps and logic will follow nearly identically for θ.

Marginal utility in both states of the world is controlled by risk effects and the sign of the random variables. Given θ is independent of ω, the expected value of $\mathbb{E}[\theta|\omega \lesseqgtr \bar{\omega}] = 0$. The difference in expected marginal profit across insurance states is defined as:

$$
\begin{aligned}
\frac{\partial \mathbb{E}[\pi|\omega < \bar{\omega}]}{\partial x_m^*} - \frac{\partial \mathbb{E}[\pi|\omega > \bar{\omega}]}{\partial x_m^*} =& \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega < \bar{\omega}] + \cancel{f_{x_m^*}(X^*)\widehat{B}} + \cancel{\mathbb{E}[\theta f_x(X^*)|\omega < \bar{\omega}]} - \cancel{c_{x_m^*}(X^*)} \\
& - \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega > \bar{\omega}] + \cancel{f_{x_m^*}(X^*)\widehat{B}} + \cancel{\mathbb{E}[\theta f_x(X^*)|\omega > \bar{\omega}]} - \cancel{c_{x_m^*}(X^*)} \\
=& \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega < \bar{\omega}] - \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega > \bar{\omega}]
\end{aligned}
\tag{18}
$$

If an input is risk decreasing then $h_{x_m}(X) < 0$. Then Equation 18 is positive and marginal profit in the bad state is greater than the marginal profit in the good state. Adding more of a risk reducing input reduces the negative impact in the bad state relative to the good state.

$$
\frac{\partial \mathbb{E}[\pi|\omega < \bar{\omega}]}{\partial x_m^*} - \frac{\partial \mathbb{E}[\pi|\omega > \bar{\omega}]}{\partial x_m^*} = \overbrace{\mathbb{E}[\omega h_{x_m^*}(X^*)|\omega < \bar{\omega}] - \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega > \bar{\omega}]}^{+}
$$

Repeating the same steps for risk increasing inputs $h_{x_m}(X) > 0$ shows that marginal profit in the bad state is less than marginal profit in the good state.

$$
\frac{\partial \mathbb{E}[\pi|\omega < \bar{\omega}]}{\partial x_m^*} - \frac{\partial \mathbb{E}[\pi|\omega > \bar{\omega}]}{\partial x_m^*} = \overbrace{\mathbb{E}[\omega h_{x_m^*}(X^*)|\omega < \bar{\omega}] - \mathbb{E}[\omega h_{x_m^*}(X^*)|\omega > \bar{\omega}]}^{-}
$$

When the insurance contract is triggered on biological risk θ, uncorrelated shocks will always lead to higher marginal profit in the good state. Uncorrelated shocks lead $\mathbb{E}[\omega|\theta \lesseqgtr \bar{\theta}] = 0$.

$$\begin{aligned}\frac{\partial \mathbb{E}[\pi|\theta<\bar{\theta}]}{\partial x_m^*}-\frac{\partial \mathbb{E}[\pi|\theta>\bar{\theta}]}{\partial x_m^*} =&\cancel{\mathbb{E}[\omega h_{x_m^*}(X^*)|\theta<\bar{\theta}]}+\cancel{f_{x_m^*}(X^*)\hat{B}}+\mathbb{E}[\theta f_x(X^*)|\theta<\bar{\theta}]-\cancel{c_{x_m^*}(X^*)}\\ &-\cancel{\mathbb{E}[\omega h_{x_m^*}(X^*)|\theta>\bar{\theta}]}-\cancel{f_{x_m^*}(X^*)\hat{B}}-\mathbb{E}[\theta f_x(X^*)|\theta>\bar{\theta}]+\cancel{c_{x_m^*}(X^*)}\\ =&\mathbb{E}[\theta f_x(X^*)|\theta<\bar{\theta}]-\mathbb{E}[\theta f_x(X^*)|\theta>\bar{\theta}]\end{aligned} \tag{19}$$

The concavity of $f(X)$ leads to $f_x(X) > 0$ always. Equation 19 can then be signed to always be negative so that marginal profit in the good state is always higher when insurance contracts are triggered on θ.

$$\frac{\partial \mathbb{E}[\pi|\theta<\bar{\theta}]}{\partial x_m^*}-\frac{\partial \mathbb{E}[\pi|\theta>\bar{\theta}]}{\partial x_m^*}=\overbrace{\mathbb{E}[\theta f_{x_m^*}(X^*)|\theta<\bar{\theta}]-\mathbb{E}[\theta f_{x_m^*}(X^*)|\theta>\bar{\theta}]}^{-}$$

□

A.2 Proof of Lemma 3.2

Lemma 3.2 *When shocks are perfectly correlated, expected marginal profit is always higher in the good state when an input, x_m, is risk increasing and ambiguous when x_m is risk decreasing. This hold regardless of the chosen index.*

$\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x_m}-\frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x_m}<0$ *if* $h_{x_m}(X)>0$

And, $\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x_m}-\frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x_m}\lesseqgtr 0$ *if* $h_{x_m}(X)<0$.

Proof. Perfect correlation between two random variables centered at 0 imply that whenever one variable is negative, so too is the other. Due to this, we focus only on ω as the index. The proof follows identically if replaced by an index on θ.

$$\begin{aligned}\frac{\partial \mathbb{E}[\pi|\omega<\bar{\omega}]}{\partial x}-\frac{\partial \mathbb{E}[\pi|\omega>\bar{\omega}]}{\partial x}=&\cancel{f_x(x)}\hat{B}+\mathbb{E}[\theta f_x(x)|\omega<\bar{\omega}]+\mathbb{E}[\omega h_x(x)|\omega<\bar{\omega}]-\cancel{c}(x)\\ &-\cancel{f_x(x)}\hat{B}+\mathbb{E}[\theta f_x(x)|\omega>\bar{\omega}]+\mathbb{E}[\omega h_x(x)|\omega>\bar{\omega}]-\cancel{c}(x)\end{aligned} \tag{20}$$

When $h_x(X) > 0$, Equation 20 is always negative. Expected marginal profit is always higher in the good trigger state when shocks are perfectly correlated.

When $h_x(X) < 0$, Equation 20 is ambiguous. The sign of each line depends on the relative effect between $f_x(X)$ and $h_x(X)$. If the risk effects term dominates then Equation 20 will be positive. Without further information it is impossible to know which effect dominates. □

A.3 Proof of Proposition 4.1

Proposition 4.1 *In fisheries with two inputs, when θ and ω are uncorrelated, index insurance will change the optimal use of a specific input in accordance to an input's own risk effect when the following sufficient condition is true:*

$\frac{\partial U}{\partial x_a x_b} > 0$ *when both inputs share the same risk effects, and* $\frac{\partial U}{\partial x_a \partial x_b} < 0$ *when inputs have opposite risk effects*

Otherwise, index insurance will have ambiguous effects on optimal input choice.

Proof. We use the same insurance design from Section 3. Fishers now maximize expected utility by selecting two inputs. Contracts are built on ω, but all steps follow for θ.

$$\begin{aligned} U \equiv \max_{x_a, x_b} \mathbb{E}[U] = \int_{-\infty}^{\infty} \Bigg[& \int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta) u(\pi(X, \hat{B}, \theta, \omega) + (1 - J(\bar{\omega}))\gamma) d\omega \\ & + \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta) u(\pi(X, \hat{B}, \theta, \omega) - J(\bar{\omega})\gamma) d\omega \Bigg] d\theta \end{aligned} \tag{21}$$

Taking the first order conditions yields:

$$\begin{aligned} \frac{\partial U}{\partial x_a} &= \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta) u_{x_a}(\pi(X, \hat{B}, \theta, \omega) + (1 - J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x_a}(X, \hat{B}, \theta, \omega) d\omega \\ &\quad + \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta) u_{x_a}(\pi(X, \hat{B}, \theta, \omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x_a}(X, \hat{B}, \theta, \omega) d\omega \Bigg] d\theta \\ &= 0 \\ \frac{\partial U}{\partial x_b} &= \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta) u_{x_b}(\pi(X, \hat{B}, \theta, \omega) + (1 - J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x_b}(X, \hat{B}, \theta, \omega) d\omega \\ &\quad + \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta) u_{x_b}(\pi(X, \hat{B}, \theta, \omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x_b}(X, \hat{B}, \theta, \omega) d\omega \Bigg] d\theta \\ &= 0 \end{aligned} \tag{22}$$

Assuming the first order condition is satisfied, we can use the implicit function theorem (IFT) to look at the impact of a change in the exogenous insurance contract. Applying IFT yields a system of equations that determine the impact of insurance on each optimal input:

$$\begin{aligned} \frac{\partial x_a}{\partial \gamma} &= \frac{-1}{Det} \left[\frac{\partial U}{\partial x_b \partial x_b} \frac{\partial U}{\partial x_a \partial \gamma} - \frac{\partial U}{\partial x_a \partial x_b} \frac{\partial U}{\partial x_b \partial \gamma} \right] \\ \frac{\partial x_b}{\partial \gamma} &= \frac{-1}{Det} \left[\frac{-\partial U}{\partial x_b \partial x_a} \frac{\partial U}{\partial x_a \partial \gamma} + \frac{\partial U}{\partial x_a \partial x_a} \frac{\partial U}{\partial x_b \partial \gamma} \right] \end{aligned} \tag{23}$$

Because the DET will always be positive by the second-order condition, we can focus on the interior of the brackets. If positive, then insurance will lower use of that specific input and vice versa. The partial derivatives in Equation 23 are complex. Their complete derivations are included in Section A.4.

Lemma 3.1 allows us to sign the partial equations Equation 29 and Equation 30 for any risk effect on either input. Concave utility by definition leads to $u'' < 0$. For simplicity, we will only focus on $\frac{\partial U}{\partial x_a \partial \gamma}$, but all applies equally to $\frac{\partial U}{\partial x_b \partial \gamma}$. Insurance payouts equalize profits between different states. If insurance completely covers all loss and x_a is risk increasing, then $\frac{\partial U}{\partial x_a \partial \gamma}$ is positive.

$$\begin{aligned}\frac{U}{\partial x_a \partial \gamma} = \int_{-\infty}^{\infty} & \overbrace{j_\theta(\theta) J(\bar{\theta})(1 - J(\bar{\theta})) u''(\theta, \cdot)}^{-} \\ & \left[\underbrace{\int_{-\infty}^{\bar{\omega}} j_\omega(\omega) \frac{\partial \pi}{\partial x_a} d\omega - \int_{\bar{\theta}}^{\infty} j_\omega(\omega) \frac{\partial \pi}{\partial x_a} d\omega}_{-} \right] d\theta \\ > 0 &\end{aligned} \tag{24}$$

Suppose both inputs are risk increasing so $\frac{\partial U}{\partial x_a \partial \gamma}$ and $\frac{\partial U}{\partial x_b \partial \gamma}$ are positive. The only way for Equation 23 to be unambiguously positive is for $\frac{\partial U}{\partial x_a \partial x_b}$ and $\frac{\partial U}{\partial x_a \partial x_b}$ to be positive.

$$\frac{\partial x_a}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{\partial U}{\partial x_b \partial x_b}}^{-} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} - \overbrace{\frac{\partial U}{\partial x_a \partial x_b}}^{-} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{+}}^{-} \right] > 0$$

$$\frac{\partial x_b}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{-\partial U}{\partial x_b \partial x_a}}^{-} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} + \overbrace{\frac{\partial U}{\partial x_a \partial x_a}}^{-} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{+}}^{-} \right] > 0$$

Both risk increasing inputs will be raised with index insurance. Repeating the same steps above with risk decreasing inputs shows both inputs unambiguously decrease with index insurance.

Now suppose inputs have mixed risk effects. For simplicity, x_a will be risk increasing and x_b will be risk decreasing. The results will hold for the opposite case. By Lemma 3.1, $\frac{\partial U}{\partial x_a \partial \gamma}$ is positive, while $\frac{\partial U}{\partial x_b \partial \gamma}$ is negative. Equation 23 will be unambiguously positive if $\frac{\partial U}{\partial x_a \partial x_b}$ and $\frac{\partial U}{\partial x_b \partial x_a}$ are negative.

$$\frac{\partial x_a}{\partial \gamma} = \frac{\overbrace{-1}^{-}}{Det}\left[\overbrace{\overbrace{\frac{\partial U}{\partial x_b \partial x_b}}^{-}\overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} - \overbrace{\frac{\partial U}{\partial x_a \partial x_b}}^{+}\overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{-}}^{-}\right] > 0$$

$$\frac{\partial x_b}{\partial \gamma} = \frac{\overbrace{-1}^{-}}{Det}\left[\overbrace{\overbrace{\frac{-\partial U}{\partial x_b \partial x_a}}^{+}\overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} + \overbrace{\frac{\partial U}{\partial x_a \partial x_a}}^{-}\overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{-}}^{+}\right] < 0$$

The risk increasing input will be raised with index insurance, while the risk decreasing input will be lowered.

If these conditions do not hold, then it is impossible to determine which additive element outweighs the other, and the insurance effects on optimal input use will be ambiguous regardless of the underlying risk effects of an input. □

A.4 Partial derivatives

Partial derivatives used to sign Equation 23 are shown below. For brevity, $\pi(X, \hat{B}, \omega, \theta)$ is reduced to π.

$$\frac{\partial U}{\partial x_a \partial x_a} = \int_{-\infty}^{\infty}\left[\int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta)[u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a} + u'(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a x_a}]d\omega \right. \\ \left. + \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta)[u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a} + u'(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a x_a}]d\omega\right] d\theta \tag{25}$$

$$\frac{\partial U}{\partial x_b \partial x_b} = \int_{-\infty}^{\infty}\left[\int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta)[u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_b} + u'(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_b x_b}]d\omega \right. \\ \left. \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta)[u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_b} + u'(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_b x_b}]d\omega\right] d\theta \tag{26}$$

$$\frac{\partial U}{\partial x_a \partial x_b} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta)[u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a x_b}]d\omega \right.$$
$$\left. \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta)[u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a x_b}]d\omega \right] d\theta \tag{27}$$

$$\frac{\partial U}{\partial x_b \partial x_a} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta)[u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_b x_a}]d\omega \right.$$
$$\left. \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta)[u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_b x_a}]d\omega \right] d\theta \tag{28}$$

$$\begin{aligned} \frac{\partial U}{\partial x_a \partial \gamma} = \int_{-\infty}^{\infty} &\left[\int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta)u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a}(1-J(\bar{\omega})d\omega \right. \\ &\left. \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta)u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a}(-J(\bar{\omega}))d\omega \right] d\theta \end{aligned} \tag{29}$$

$$\begin{aligned} \frac{\partial U}{\partial x_b \partial \gamma} = \int_{-\infty}^{\infty} &\left[\int_{-\infty}^{\bar{\omega}} j_{\omega,\theta}(\omega,\theta)u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_b}(1-J(\bar{\omega})d\omega \right. \\ &\left. \int_{\bar{\omega}}^{\infty} j_{\omega,\theta}(\omega,\theta)u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_b}(-J(\bar{\omega}))d\omega \right] d\theta \end{aligned} \tag{30}$$

A.5 Figures

References

Alvarez, A., Schmidt, P., Alvarez, A. and Schmidt, P. (2006) Is skill more important than luck in explaining fish catches? *J Prod Anal* **26**, 15–25.

Asche, F., Cojocaru, A.L., Pincinato, R.B.M. and Roll, K.H. (2020) Production risk in the norwegian fisheries. *Environmental and Resource Economics* **75**, 137–149.

Babcock, B.A. and Hennessy, D.A. (1996) Input demand under yield and revenue insurance. *American Journal of Agricultural Economics* **78**, 416–427.

Barbeaux, S.J., Holsman, K. and Zador, S. (2020) Marine heatwave stress test of ecosystem-based fisheries management in the gulf of alaska pacific cod fishery. *Frontiers in Marine Science* **7**, 1–21.

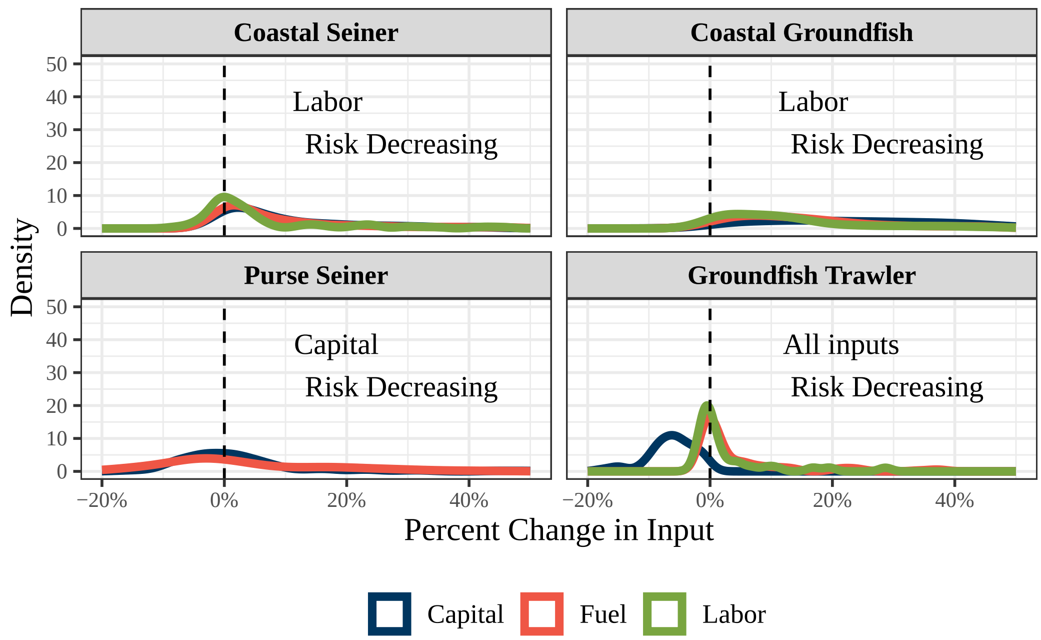

Figure A1: Density plots of the percent change in input use for each vessel type in Norwegian fisheries. The dashed black line represents no change in input use. Risk decreasing inputs are labeled. Labor (green lines) is dropped for Purse Seiners because labor was never used in simulations due to negative productivity elasticity. Entire parameter space with correlations equal to 0, 0.5, and 1 used.

Binswanger-Mkhize, H.P. (2012) Is there too much hype about index-based agricultural insurance? *Journal of Development Studies* **48**, 187–200.

Bulte, E. and Haagsma, R. (2021) The welfare effects of index-based livestock insurance: Livestock herding on communal lands. *Environmental and Resource Economics* **78**, 587–613.

Cai, J. (2016) The impact of insurance provision on household production and financial decisions. *American Economic Journal: Economic Policy* **8**, 44–88.

Carter, M., Janvry, A.D., Sadoulet, E. and Sarris, A. (2017) Index insurance for developing country agriculture: A reassessment. *Annual Review of Resource Economics* **9**, 421–438.

Cavole, L.M., Demko, A.M., Diner, R.E., et al. (2016) Biological impacts of the 2013–2015 warm-water anomaly in the northeast pacific: Winners, losers, and the future. *Oceanography* **29**, 273–285.

Cheung, W.W.L., Frölicher, T.L., Lam, V.W.Y., et al. (2021) Marine high temperature extremes amplify the impacts of climate change on fish and fisheries. *Sci. Adv* **7**.

Claassen, R., Langpap, C. and Wu, J. (2017) Impacts of federal crop insurance on land use and environmental quality. *American Journal of Agricultural Economics* **99**, 592–613.

Clarke, D.J. (2016) A theory of rational demand for index insurance. *Journal: Microeconomics* **8**, 283–306.

Collier, B., Skees, J. and Barnett, B. (2009) Weather index insurance and climate change: Opportunities and challenges in lower income countries. *Geneva Papers on Risk and Insurance: Issues and Practice* **34**, 401–424.

Deryugina, T. and Konar, M. (2017) Impacts of crop insurance on water withdrawals for irrigation. *Advances in Water Resources* **110**, 437–444.

Dougherty, J.P., Gallenstein, R.A. and Mishra, K. (2021) Impact of index insurance on moral hazard in the agricultural credit market: Theory and evidence from ghana. *Journal of African Economies* **00**, 1–31.

Eggert, H. and Tveteras, R. (2004) Stochastic production and heterogeneous risk preferences: Commercial fishers' gear choices. *American Journal of Agricultural Economics* **86**, 199–212.

Elabed, G. and Carter, M. (2018) Ex-ante impacts of agricultural insurance: Evidence from a field experiment in mali.

FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action. *INFORM* **32**.

FAO (2022) World review of capture fisheries and aquaculture insurance 2022.

Fisher, E., Hellin, J., Greatrex, H. and Jensen, N. (2019) Index insurance and climate risk management: Addressing social equity. *Development Policy Review* **37**, 581–602.

Goodwin, B.K., Vandeveer, M.L. and Deal, J.L. (2004) An empirical analysis of acreage effects of participation in the federal crop insurance program. *American Journal of Agricultural Economics* **86**, 1058–1077.

Grassini, P., Thorburn, J., Burr, C. and Cassman, K.G. (2011) High-yield irrigated maize in the western u.s. Corn belt: I. On-farm yield, yield potential, and impact of agronomic practices. *Field Crops Research* **120**, 142–150.

He, J., Zheng, X., Rejesus, R. and Yorobe, J. (2020) Input use under cost-of-production crop insurance: Theory and evidence. *Agricultural Economics (United Kingdom)* **51**, 343–357.

Heck, N., Beck, M.W. and Reguero, B. (2021) Storm risk and marine fisheries: A global assessment. *Marine Policy* **132**, 104698.

Herrmann, M., Greenberg, J., Hamel, C. and Geier, H. (2004) Extending federal crop insurance programs to commercial fisheries: The case of bristol bay, alaska, sockeye salmon. *North American Journal of Fisheries Management* **24**, 352–366.

Holland, D.S. (2008) Are fishermen rational? A fishing expedition. *Marine Resource Economics* **23**, 325–344.

Horowitz, J. and Lichtenberg, E. (1993) Insurance, moral hazard, and chemical use in agriculture. *American Journal of Agricultral Economics* **75**, 926–935.

Jardine, S.L., Fisher, M.C., Moore, S.K. and Samhouri, J.F. (2020) Inequality in the economic impacts from climate shocks in fisheries: The case of harmful algal blooms. *Ecological Economics* **176**.

John, F., Toth, R., Frank, K., Groeneveld, J. and Müller, B. (2019) Ecological vulnerability through insurance? Potential unintended consequences of livestock drought insurance. *Ecological Economics* **157**, 357–368.

Just, R.E. and Pope, R.D. (1978) Stochastic specification of production functions and economic implications. *Journal of Econometrics* **7**, 67–86.

Kasperski, S. and Holland, D.S. (2013) Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 2076–2081.

Kirkley, J. and Strand, I.E. (1998) Characterizing managerial skill and technical efficiency in a fishery. *Journal of Productivity Analysis* **9**, 145–160.

Kompas, T., Che, T.N. and Grafton, R.Q. (2004) Technical efficiency effects of input controls: Evidence from australia's banana prawn fishery. *Applied Economics* **36**, 1631–1641.

Lichtenberg, E. and Iglesias, E. (2022) Index insurance and basis risk: A reconsideration. *Journal of Development Economics* **158**.

Mahul, O. (2001) Optimal insurance against climatic experience. *American Journal of Agricultural Economics* **83**, 593–604.

Maltby, K.M., Acosta, L., Townhill, B., Touza, J., White, P. and Mangi, S.C. (2023) Exploring fishers' perceptions of index insurance and coral reef health in the context of climate-driven changes in extreme events. *ICES Journal of Marine Science* **80**, 2210–2221.

Merino, G., Urtizberea, A., Fu, D., et al. (2022) Investigating trends in process error as a diagnostic for integrated fisheries stock assessments. *Fisheries Research* **256**.

Mesterton-Gibbons, M. (1993) Game-theoretic resource modeling. *Natural Resource Modeling* **7**, 93–147.

Mishra, A.K., Nimon, R.W. and El-Osta, H.S. (2005) Is moral hazard good for the environment? Revenue insurance and chemical input use. *Journal of Environmental Management* **74**, 11–20.

Müller, B., Johnson, L. and Kreuer, D. (2017) Maladaptive outcomes of climate insurance in agriculture. *Global Environmental Change* **46**, 23–33.

Müller, B., Quaas, M.F., Frank, K. and Baumgärtner, S. (2011) Pitfalls and potential of institutional change: Rain-index insurance and the sustainability of rangeland management. *Ecological Economics* **70**, 2137–2144.

Mumford, J.D., Leach, A.W., Levontin, P. and Kell, L.T. (2009) Insurance mechanisms to mediate economic risks in marine fisheries. *ICES Journal of Marine Science* **66**, 950–959.

Murkowski, L. (2022) Working waterfronts framework: A plan to grow and support alaska's coastal and river communities.

Oken, K.L., Holland, D.S. and Punt, A.E. (2021) The effects of population synchrony, life history, and access constraints on benefits from fishing portfolios. *Ecological Applications* **0**, 1–16.

Outreville, J.F. (2014) Risk aversion, risk behavior, and demand for insurance: A survey. *Source: Journal of Insurance Issues* **37**, 158–186.

Pandori, L.L.M. and Sorte, C.J.B. (2019) The weakest link: Sensitivity to climate extremes across life stages of marine invertebrates. *Oikos* **128**, 621–629.

Pfeiffer, L. (2020) How storms affect fishers' decisions about going to sea. *ICES Journal of Marine Science* **77**, 2753–2762.

Pfeiffer, L., Petesch, T. and Vasan, T. (2022) A safer catch? The role of fisheries management in fishing safety. *Marine Resource Economics* **37**, 1–33.

Quaas, M.F. and Baumgärtner, S. (2008) Natural vs. Financial insurance in the management of public-good ecosystems. *Ecological Economics* **65**, 397–406.

Ramaswami, B. (1993) Supply response to agricultural insurance: Risk reduction and moral hazard effects. *American Journal of Agricultural Economics* **75**, 914–925.

RARE (2021) Insuring the ensurers: A new insurance project protects the fishers who feed the world.

Reimer, M.N., Abbott, J.K. and Wilen, J.E. (2017) Fisheries production: Management institutions, spatial choice, and the quest for policy invariance. *Marine Resource Economics* **32**, 143–168.

Rogers, L.A., Griffin, R., Young, T., Fuller, E., Martin, K.S. and Pinsky, M.L. (2019) Shifting habitats expose fishing communities to risk under climate change. *Nature Climate Change* **9**, 512–516.

Sainsbury, N.C., Turner, R.A., Townhill, B.L., Mangi, S.C. and Pinnegar, J.K. (2019) The challenges of extending climate risk insurance to fisheries. *Nature Climate Change* **9**, 896–897.

Sethi, S.A. (2010) Risk management for fisheries. *Fish and Fisheries* **11**, 341–365.

Sibiko, K.W. and Qaim, M. (2020) Weather index insurance, agricultural input use, and crop productivity in kenya. *Food Security* **12**, 151–167.

Sims, C., Horan, R.D. and Meadows, B. (2018) Come on feel the noise: Ecological foundations in stochastic bioeconomic models. *Natural Resource Modeling* **31**.

Smith, K.E., Burrows, M.T., Hobday, A.J., et al. (2023) Biological impacts of marine heatwaves. *Annual Review of Marine Science* **15**, 1–27.

Smith, M.D. and Wilen, J.E. (2005) Heterogeneous and correlated risk preferences in commercial fishermen: The perfect storm dilemma. *The Journal of Risk and Uncertainty* **31**, 1–53.

Smith, V.H. and Goodwin, B.K. (1996) Crop insurance, moral hazard, and agricultural chemical use. *The Economics of Agri-Environmental Policy* **2**, 169–179.

Stoeffler, Q., Carter, M., Guirkinger, C. and Gelade, W. (2022) The spillover impact of index insurance on agricultural investment by cotton farmers in burkina faso. *The World Bank Economic Review* **36**, 114–140.

Sumaila, U.R., Cheung, W., Dyck, A., et al. (2012) Benefits of rebuilding global marine fisheries outweigh costs. *PLoS ONE* **7**.

Sumaila, U.R., Walsh, M., Hoareau, K., et al. (2020) Ocean finance: Financing the transition to a sustainable ocean economy.

Teh, L.C.L. and Sumaila, U.R. (2013) Contribution of marine fisheries to worldwide employment. *Fish and Fisheries* **14**, 77–88.

Tilman, A.R., Levin, S. and Watson, J.R. (2018) Revenue-sharing clubs provide economic insurance and incentives for sustainability in common-pool resource systems keywords: Risk insurance social-ecological systems fisheries management sustainability complex adaptive systems agent-based model common-poo. *Journal of Theoretical Biology* **454**, 205–214.

Wabnitz, C.C.C. and Blasiak, R. (2019) The rapidly changing world of ocean finance. *Marine Policy* **107**, 103526.

Watson, J.R., Spillman, C.M., Little, L.R., Hobday, A.J. and Levin, P.S. (2023) Enhancing the resilience of blue foods to climate shocks using insurance. *ICES Journal of Marine Science* **80**, 2457–2469.

White, T.K. and Hoppe, R.A. (2012) Changing farm structure and the distribution of farm payments and federal crop insurance.

Wu, S., Goodwin, B.K. and Coble, K. (2020) Moral hazard and subsidized crop insurance. *Agricultural Economics (United Kingdom)* **51**, 131–142.